Hidden On-Shell Mediators for the Galactic Center Excess

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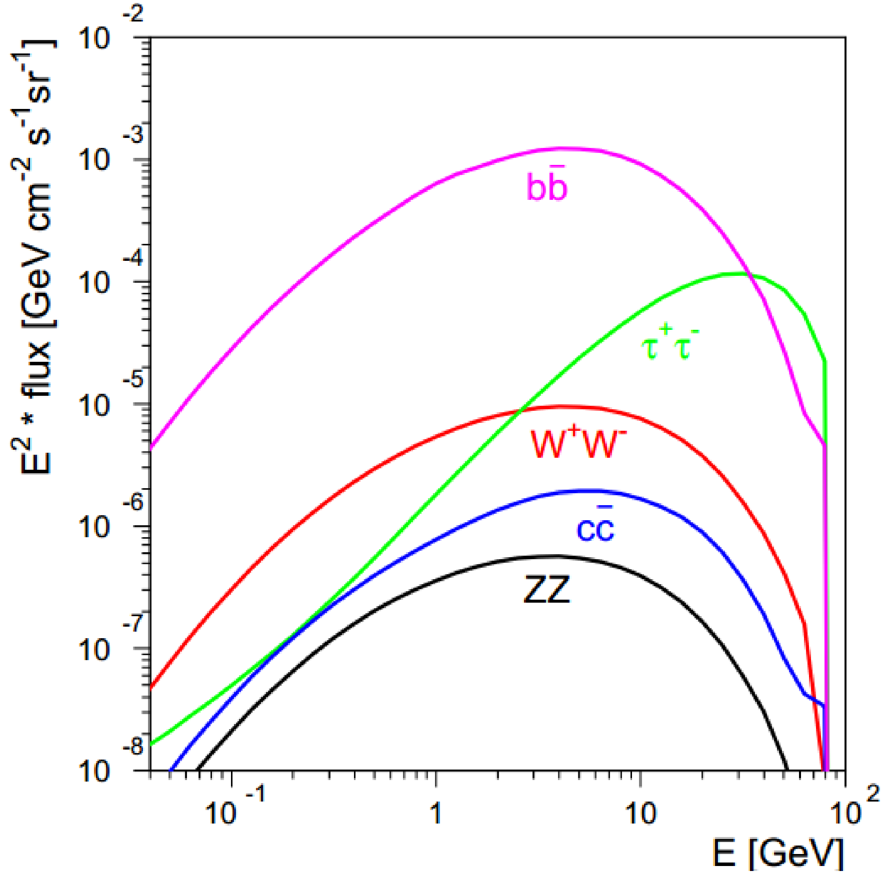
Work done with:
M. Abdullah, A. DiFranzo, A. Rajaraman,
T. M.P. Tait, P. Tanedo
arXiv:1404.6528 [hep-ph]

Outline

- What is the galactic center excess?
- Particle physics models for the galactic center
  - Mechanism to model the excess via on-shell mediators
- Parameter space for the galactic center
- Bounds on hidden, on-shell mediators
- Opportunities for future work

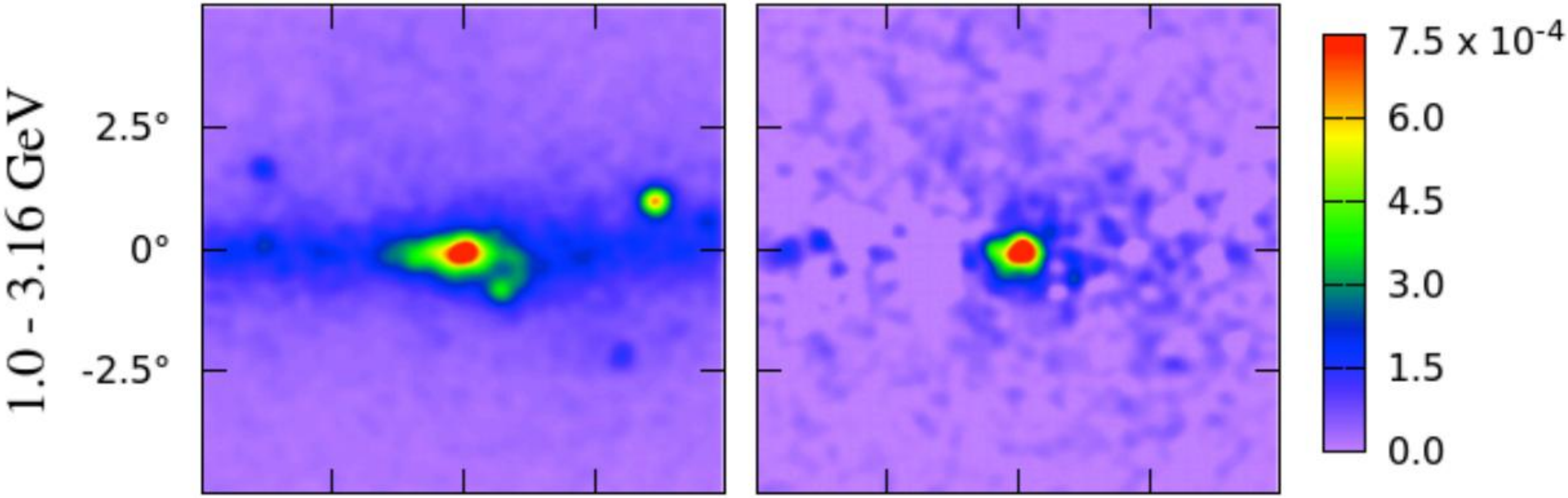
Indirect Detection

- Dark Matter may annihilate or decay into standard model particles
- Eventually, these particles become protons, electrons, neutrinos, and photons
- The photons can reach the Earth and are reliably detected.



W. de Boer, C. Sander, V. Zhukov, A. V. Gladyshev and D. I. Kazakov, "Egret excess of diffuse galactic gamma rays as tracer of dark matter," Astron. Astrophys. **444**, 51 (2005) [astro-ph/0508617].

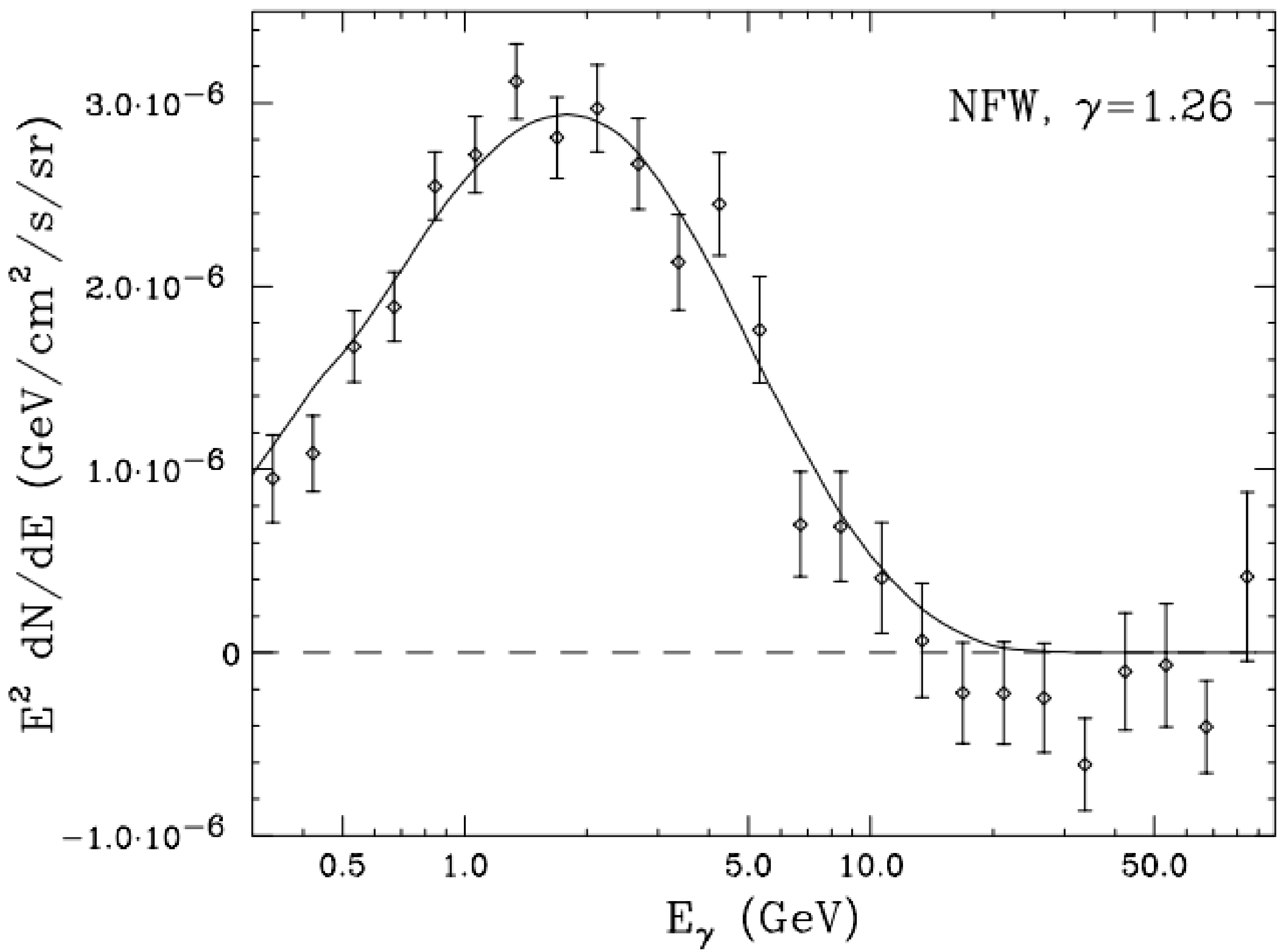
What is the Galactic Center Excess?



Total Flux　　Residual Model (x3)

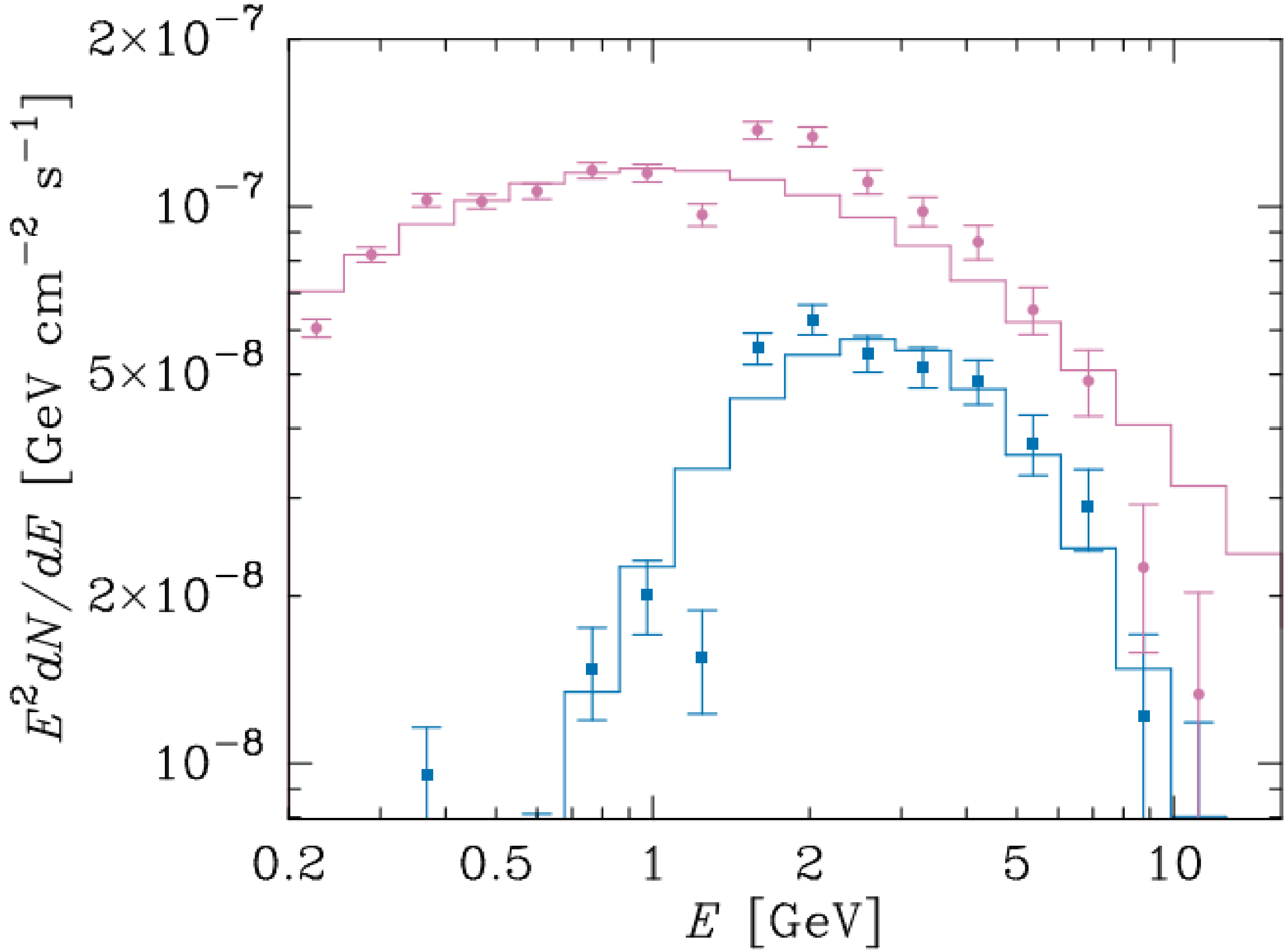
$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1+r/r_s)^{3-\gamma}}$$

T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, N.L. Rodd and T. R. Slatyer, "The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter," arXiv:1402.6703 [astro-ph.HE]



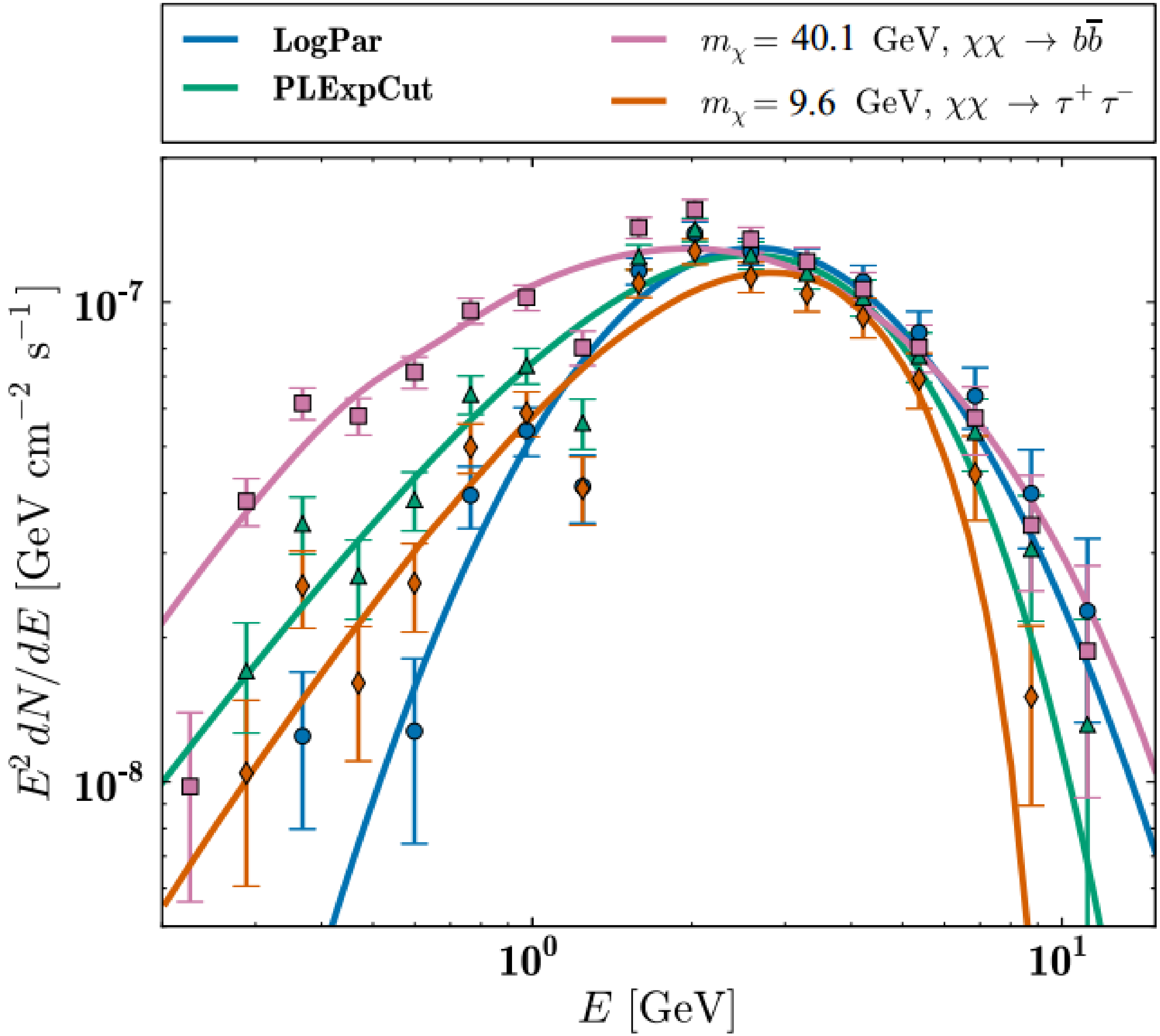
$$\sigma v = 1.7 \times 10^{-26} cm^3/s$$

T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. K. N. Portillo, N.L. Rodd and T. R. Slatyer, "The Characterization of the Gamma-Ray Signal from the Central Milky Way: A Compelling Case for Annihilating Dark Matter," arXiv:1402.6703 [astro-ph.HE]



$$\sigma v = 5.1 \times 10^{-26} cm^3/s$$

K. N. Abazajian, N. Canac, S. Horiuchi and M. Kaplinghat, "Astrophysical and Dark Matter Interpretations of Extended Gamma Ray Emission from the Galactic Center," arXiv:1402.4090 [astro-ph.HE].



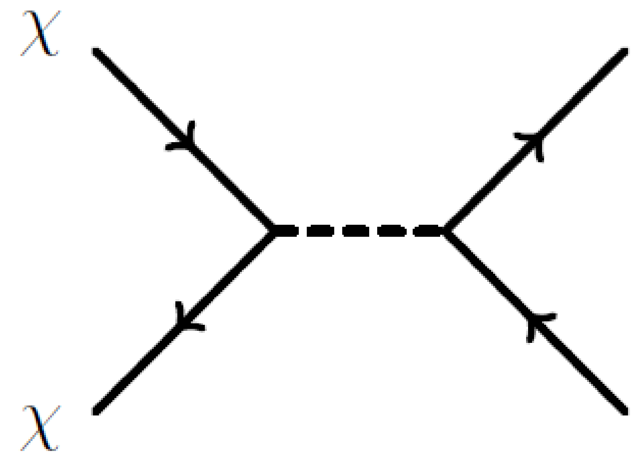
K. N. Abazajian, N. Canac, S. Horiuchi and M. Kaplinghat, “Astrophysical and Dark Matter Interpretations of Extended Gamma Ray Emission from the Galactic Center,” arXiv:1402.4090 [astro-ph.HE].

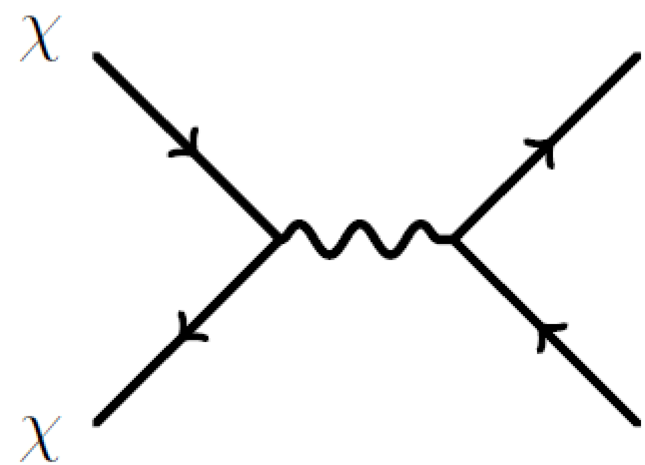
Particle Physics Models for the Galactic Center

- Inputs from the galactic center:
  - Value of σv is suggestive of thermal WIMP
  - S-wave DM annihilation
  - Annihilation should produce τ or b particles
  - The resulting τ or b should have a particular energy to reproduce the observed spectrum

Two Body Annihilation

- Two WIMPs meet and become a pair of SM particles
- Both resulting particles have the energy of the WIMP mass in the center of mass frame
- Since WIMPs are non relativistic, that frame is typically the galactic frame





Two Body Annihilation has been extensively explored

- Effective Interactions
  - A. Alves *et al.* arXiv:1403.5027 [hep-ph]
- Simplified Models
  - A. Berlin *et al.* arXiv:1404.0022 [hep-ph]
  - C. Boehm *et al.* arXiv:1401.6458 [hep-ph]
  - E. Izaguirre *et al.* arXiv:1404.2018 [hep-ph]
  - P. Agrawal *et al.* arXiv:1404.1373 [hep-ph]
- UV Models
  - S. Ipek *et al.* arXiv:1404.3716 [hep-ph]

Effective Operators

(D1)	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q$	(D8)	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
(D2)	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$	(D9)	$\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
(D3)	$\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q$	(D10)	$\frac{1}{\Lambda^2}\epsilon^{\mu\nu\alpha\beta}\bar{\chi}\sigma_{\mu\nu}\chi\bar{q}\sigma_{\alpha\beta}q$
(D4)	$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$	(D11)	$\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\chi\left(G^a_{\mu\nu}\right)^2$
(D5)	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$	(D12)	$\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\gamma^5\chi\left(G^a_{\mu\nu}\right)^2$
(D6)	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$	(D13)	$\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\chi G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$
(D7)	$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$	(D14)	$\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\gamma^5\chi G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$

Effective Operators

~~(D1)~~ $$\cancel{\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q}$$

(D2) $$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}q$$

~~(D3)~~ $$\cancel{\frac{m_q}{\Lambda^3}\bar{\chi}\chi\bar{q}\gamma^5 q}$$

(D4) $$\frac{m_q}{\Lambda^3}\bar{\chi}\gamma^5\chi\bar{q}\gamma^5 q$$

(D5) $$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$$

(D6) $$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu q$$

(D7) $$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu\gamma^5 q$$

(D8) $$\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$$

~~(D9)~~ $$\cancel{\frac{1}{\Lambda^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q}$$

~~(D10)~~ $$\cancel{\frac{1}{\Lambda^2}\epsilon^{\mu\nu\alpha\beta}\bar{\chi}\sigma_{\mu\nu}\chi\bar{q}\sigma_{\alpha\beta}q}$$

~~(D11)~~ $$\cancel{\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\chi\left(G^a_{\mu\nu}\right)^2}$$

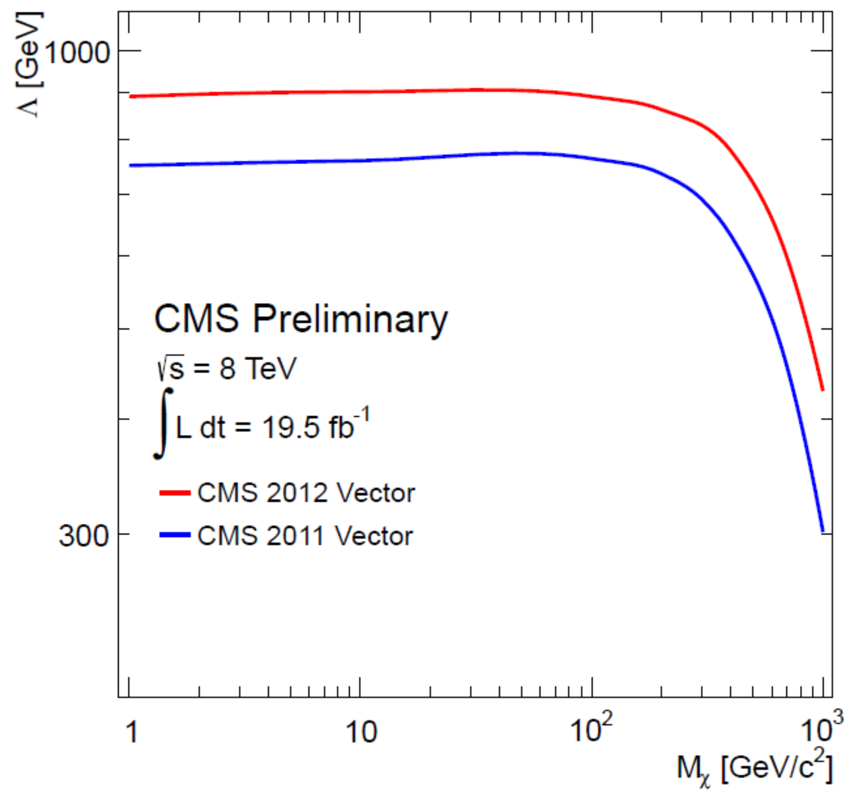
~~(D12)~~ $$\cancel{\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\gamma^5\chi\left(G^a_{\mu\nu}\right)^2}$$

~~(D13)~~ $$\cancel{\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\chi G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}}$$

~~(D14)~~ $$\cancel{\frac{\alpha_s}{4\Lambda^3}\bar{\chi}\gamma^5\chi G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}}$$

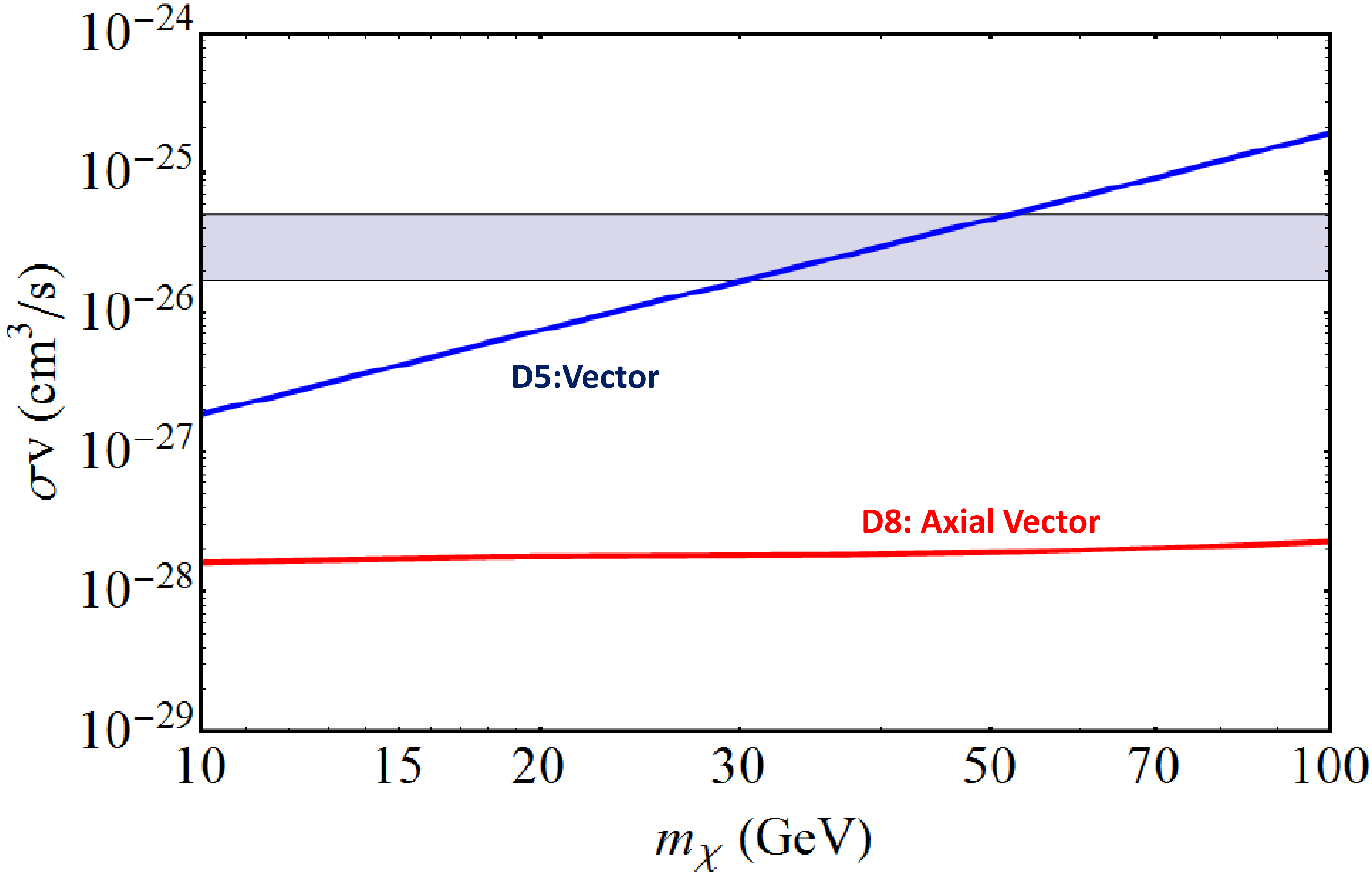
CMS Monojet Search

- Attempt to produce a WIMP pair via quark annihilation
- Detectable events occur when the pair is recoiling off QCD ISR, resulting in a single jet and MET



CMS Collaboration "Search for new physics in monojet events in pp collisions at sqrt(s)= 8 TeV" CMS-PAS-EXO-12-048

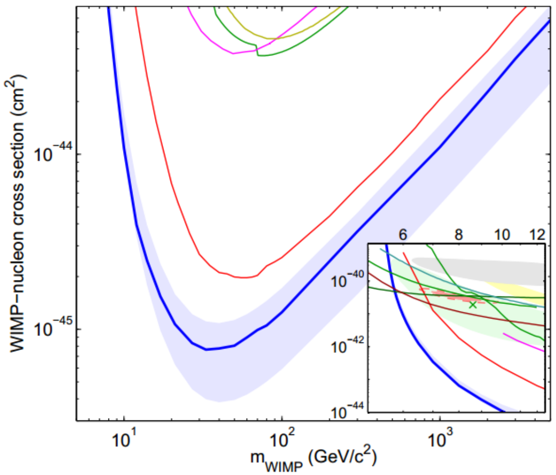
Bounds on Heavy Physics from Colliders

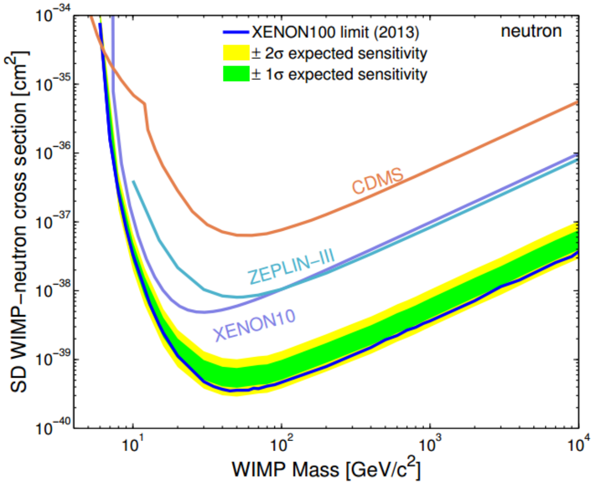


A. M. Wijangco

Direct Detection Nucleon Scattering

- Attempt to observe WIMP nucleon scattering
- This scattering may or may not be independent of the nucleus spin

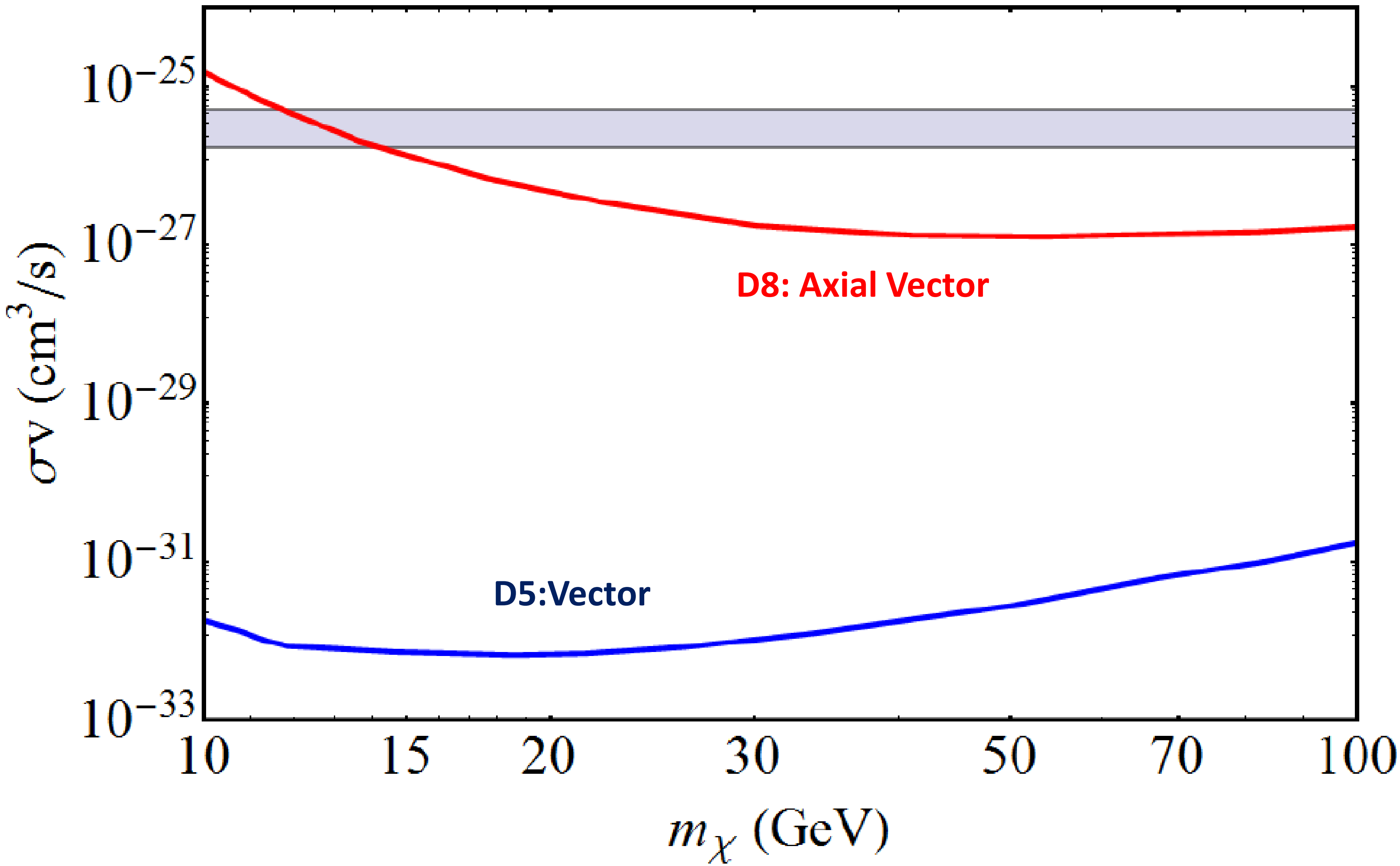




D. S. Akerib *et al.* LUX Collaboration, "First results from the LUX dark matter experiment at the Sanford Underground Research Facility," arXiv:1310.8214 [astro-ph.CO].

E. Aprile *et al.* XENON100 Collaboration, "Limits on spin-dependent WIMP-nucleon cross sections from 225 live days of XENON100 data," Phys. Rev. Lett. **111**, no. 2, 021301 (2013) [arXiv:1301.6620 [astro-ph.CO]]

Bounds from Direct Detection



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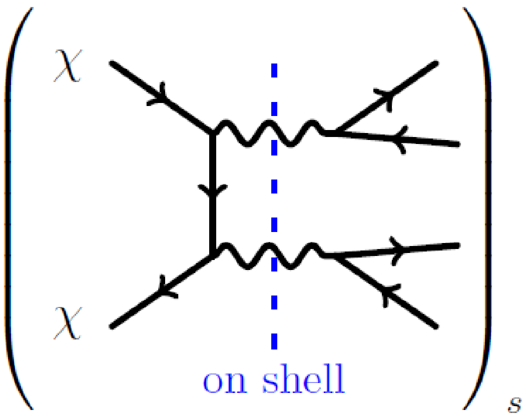
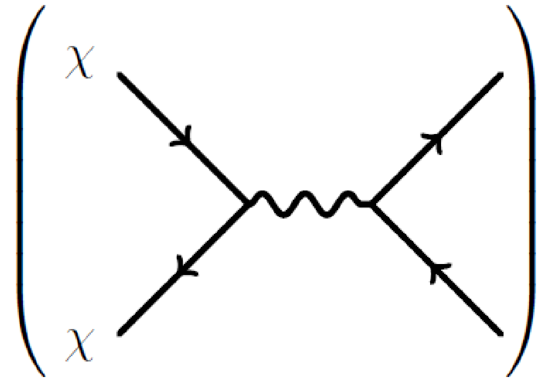
Solution: On-shell mediators

$$\mathcal{L}_{int} = \lambda_{DM} V^{\mu} \bar{\chi} \gamma_{\mu} \left(\gamma^5\right) \chi + \lambda_{SM} V^{\mu} \bar{q} \gamma_{\mu} \left(\gamma^5\right) q$$

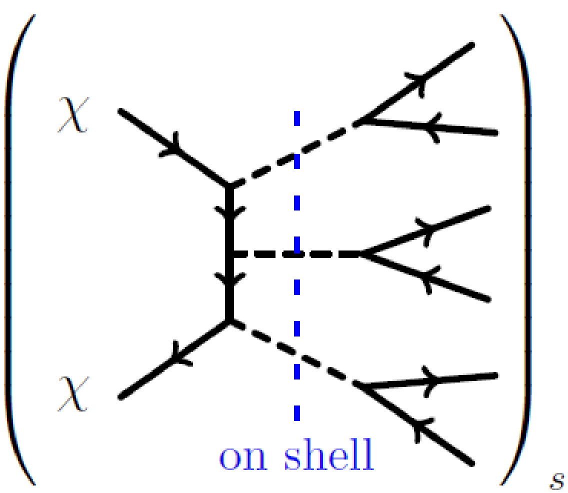


$$\sim \lambda_{\rm DM}^2 \quad \gg$$

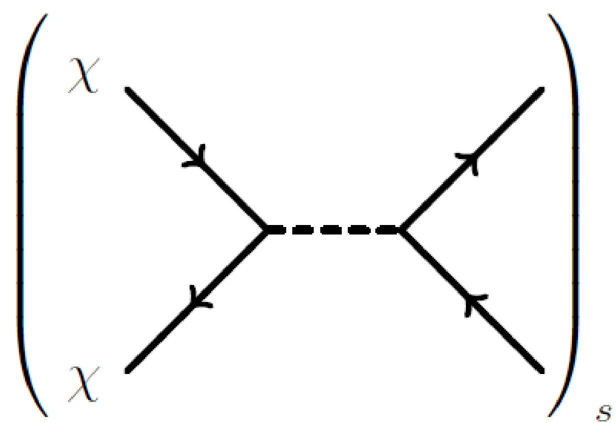


$$\sim \lambda_{\rm DM}\lambda_{\rm SM}$$

$$\mathcal{L}_{int} = \lambda_{DM} \phi \bar{\chi} \gamma^5 \chi + \lambda_{SM} \phi \bar{q}_L \left(\gamma^5\right) q_R + H.C.$$



$$\sim \frac{\lambda_{\rm DM}^3}{\sqrt{4\pi}} \quad \gg$$

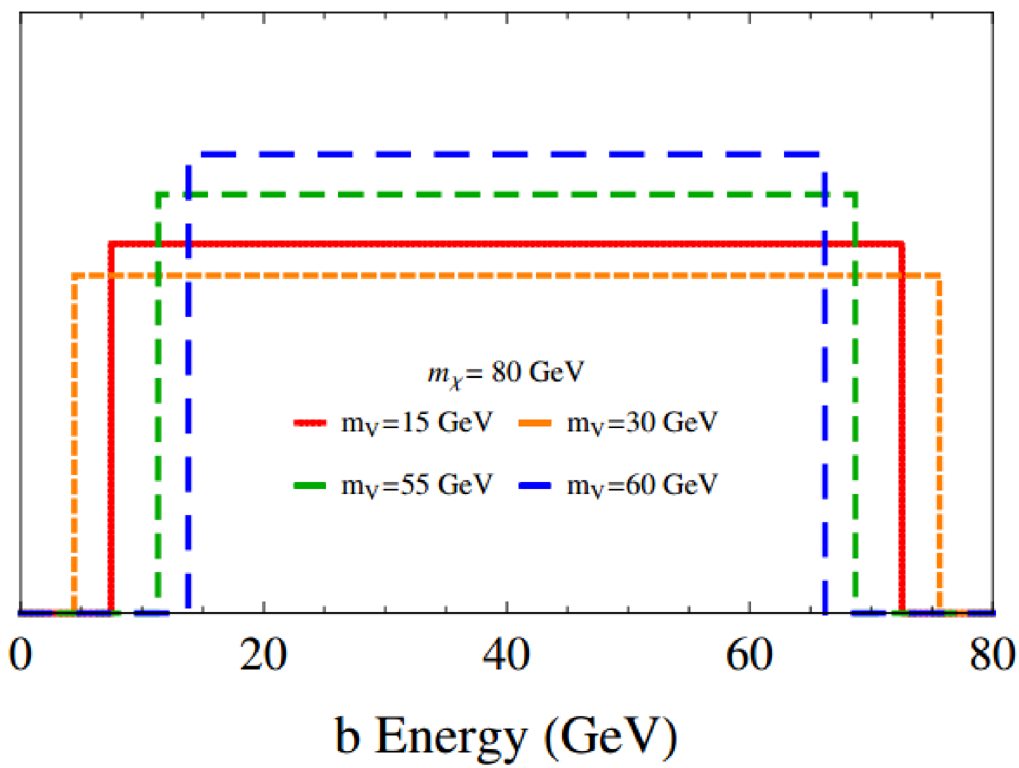


$$\sim \lambda_{\rm DM}\lambda_{\rm SM}$$

- Inputs from the galactic center:
  - Value of σv is suggestive of thermal WIMP
  - S-wave DM annihilation
  - Annihilation should produce τ or b particles
  - The resulting τ or b should have a particular energy

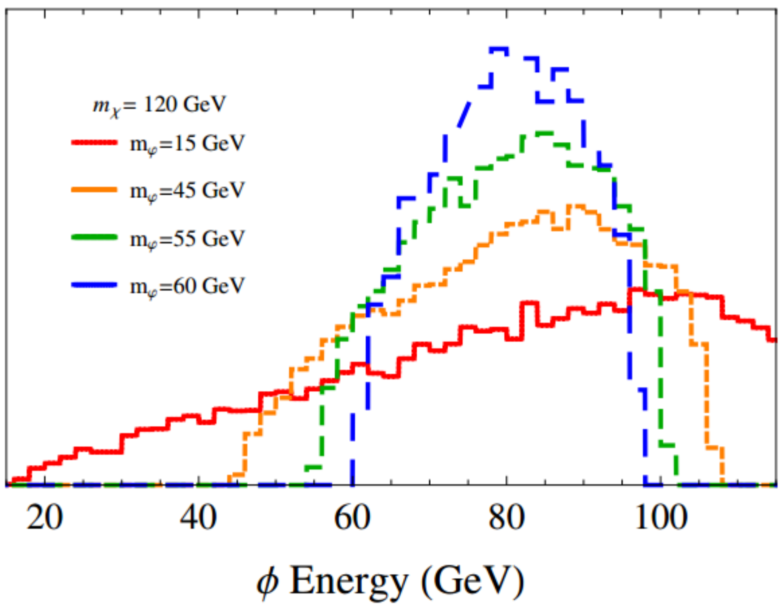
- Do on-shell mediators satisfy:
  - Allows for WIMPs, thermal relic later
  - 2 vectors or 3 pseudoscalars
  - Resulting particles controlled by mediator couplings
  - Can get 40 GeV b quarks

Spin 1 Mediator

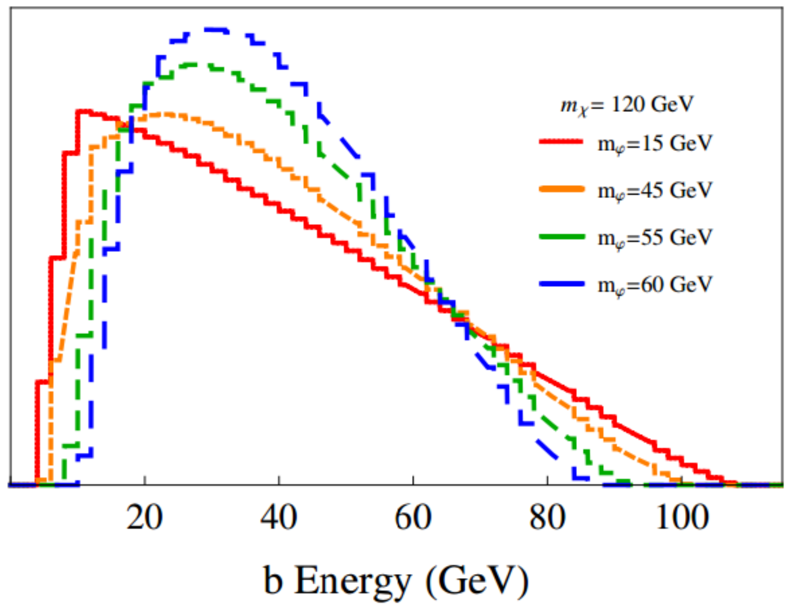


$$\chi\bar{\chi} \to VV \to 4b$$

Spin 0 Mediator



$$\chi\bar{\chi} \to 3\varphi$$



$$\chi\bar{\chi} \to 3\varphi \to 6b$$

Parameter space for the galactic center

The relevant parameters are:

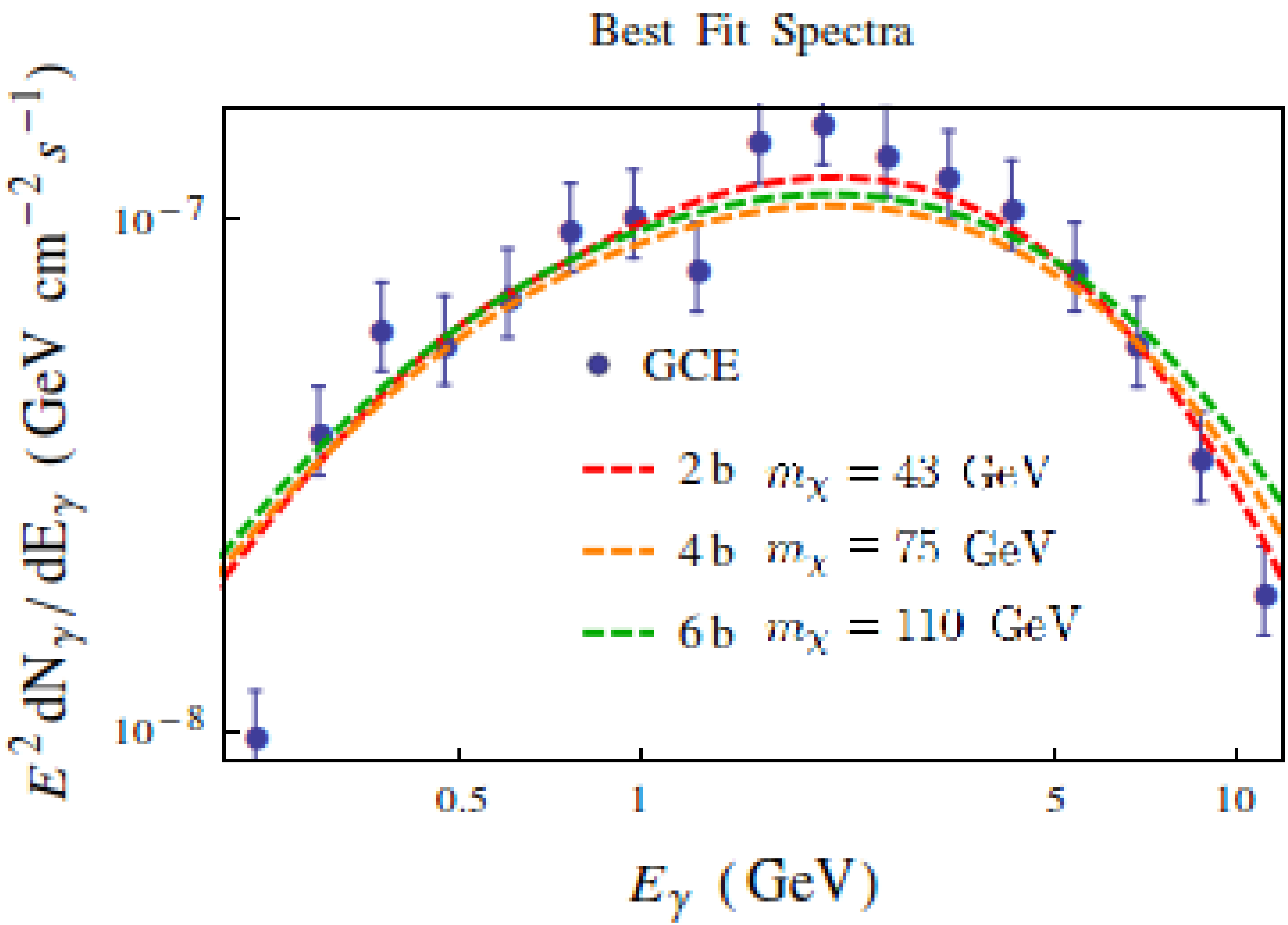
-WIMP mass: controls shape of the spectrum

-Mediator mass: controls shape of the spectrum

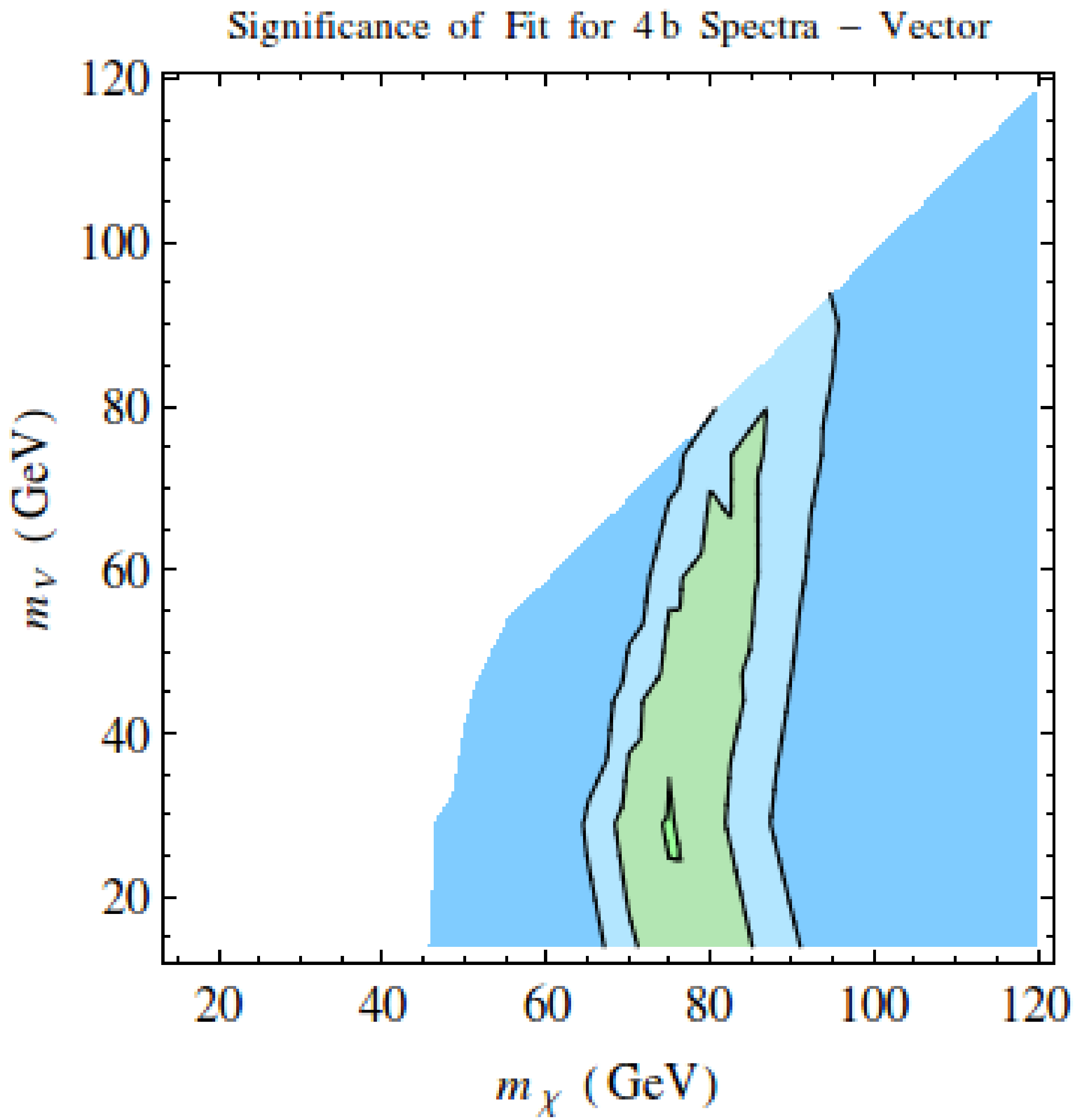
-DM Coupling: affects normalization

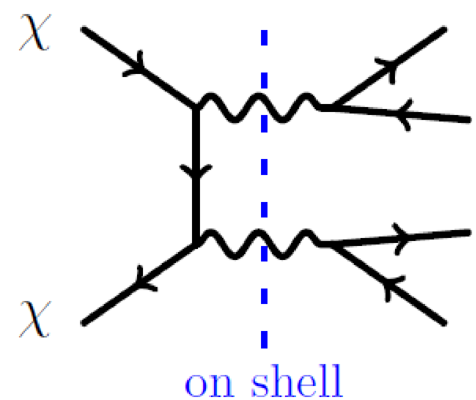
Since this fit is heavily dependent on the shape, we impose a 20% error on all residuals.

$$\text{goodness of fit} = \sum_i \left(\frac{\log D_i - \log\left(\lambda_{\mathrm{DM}}^{2n} S_i\right)}{\log(0.2 D_i)} \right)^2$$

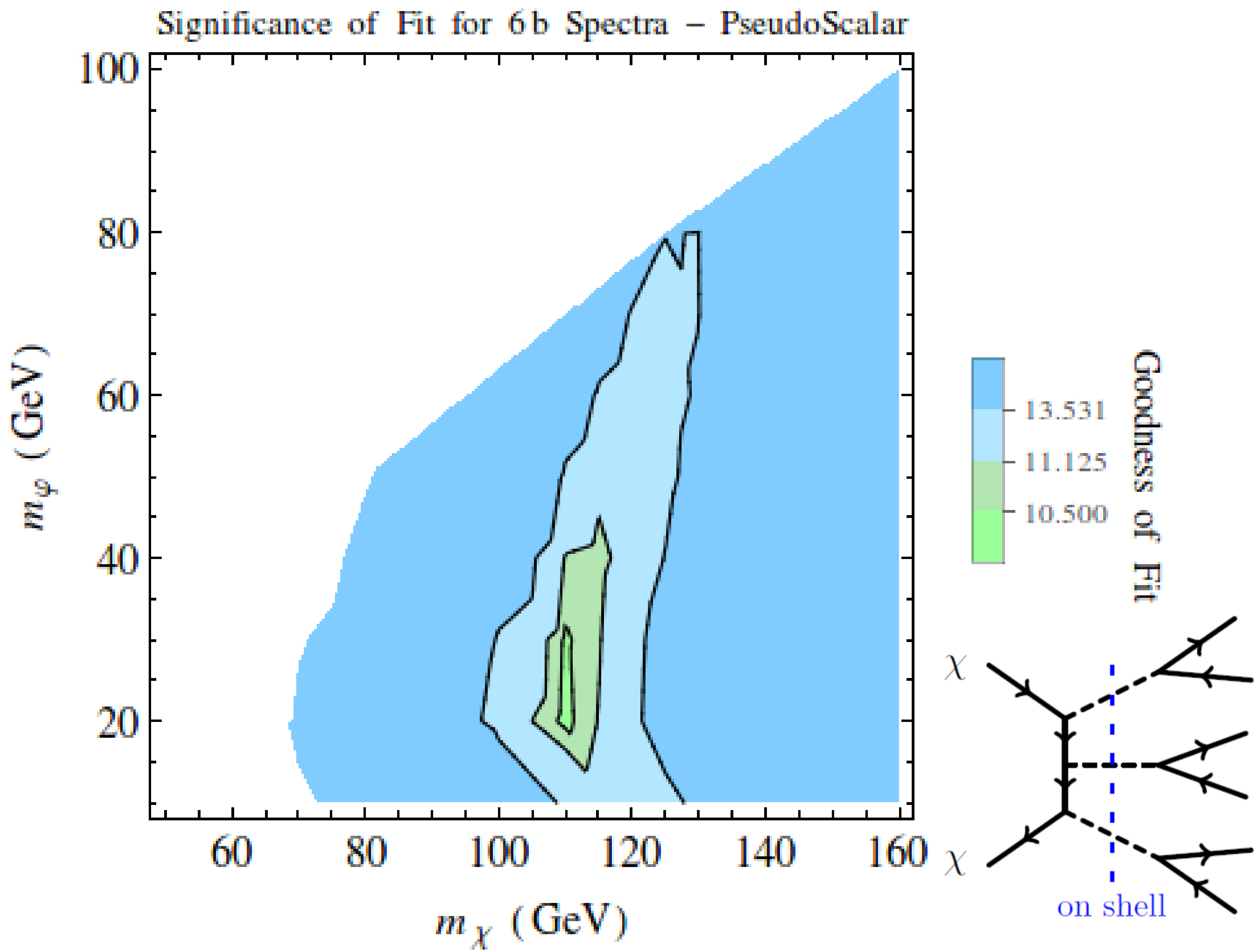


Best Fit Spectra
$E^2 dN_\gamma / dE_\gamma$ (GeV cm$^{-2}s^{-1}$)
10^{-7}
10^{-8}
0.5
1
5
10
E_γ (GeV)
GCE
2 b $m_\chi = 43$ GeV
4 b $m_\chi = 75$ GeV
6 b $m_\chi = 110$ GeV

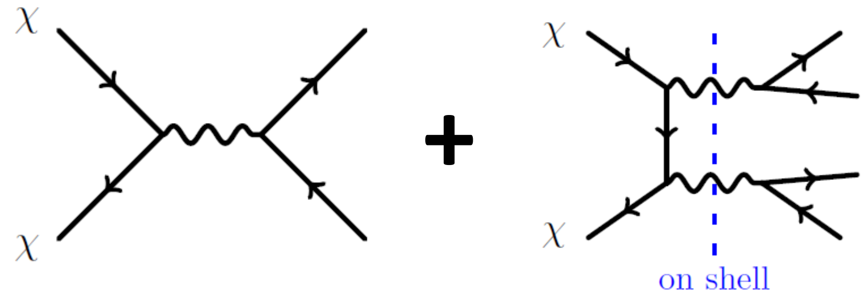




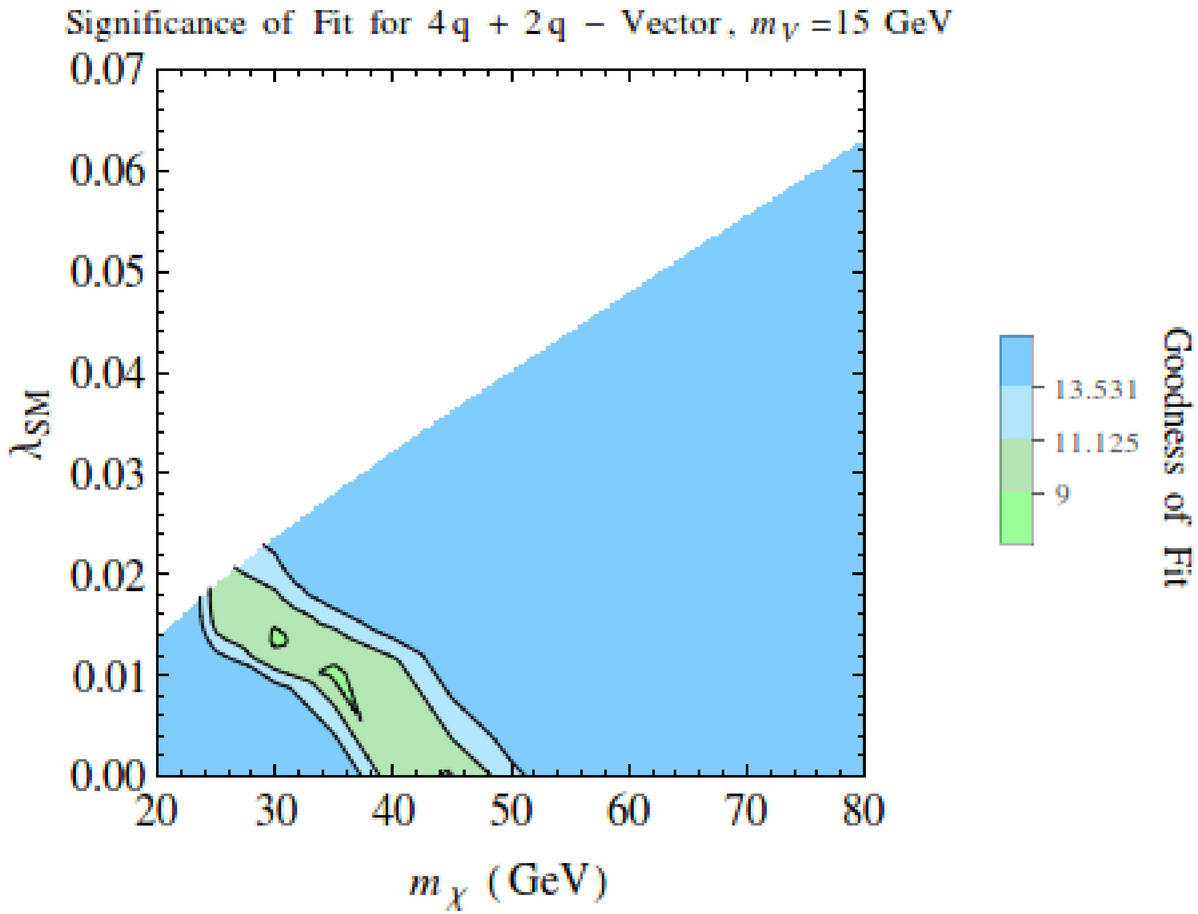
$$\lambda_{\rm DM} \sim 0.27 - 0.44$$



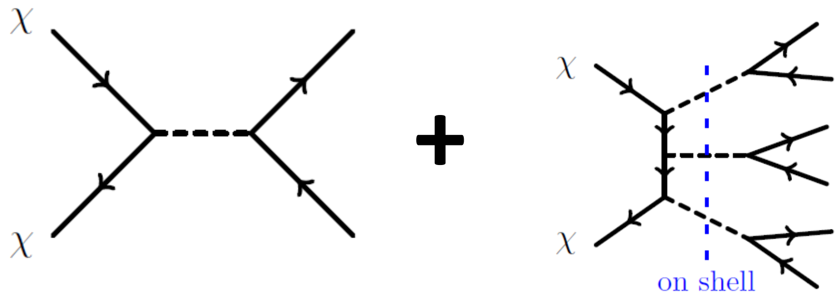
$$\lambda_{\rm DM} \sim 1.1 - 1.4$$



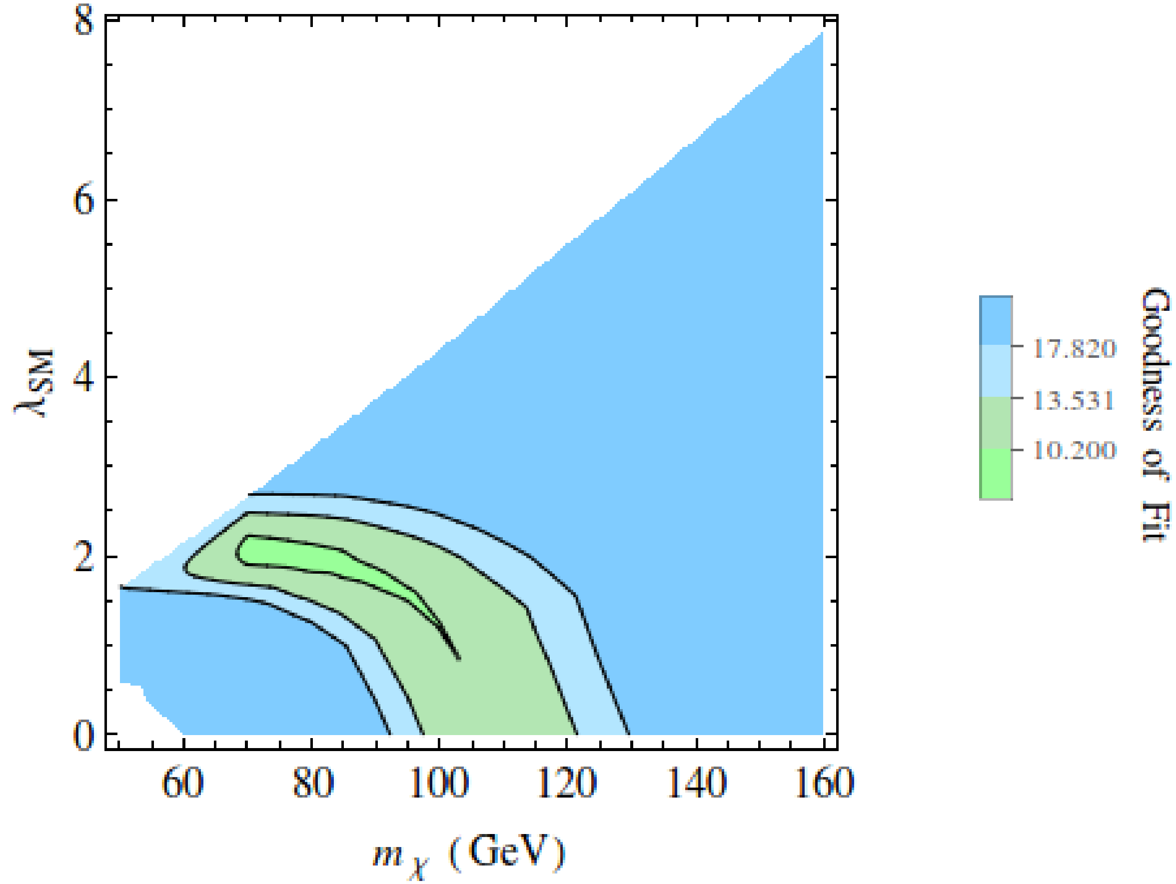
χ
χ
+
χ
χ
on shell



Significance of Fit for 4 q + 2 q − Vector, m_V =15 GeV
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
λ_{SM}
20
30
40
50
60
70
80
m_χ (GeV)
13.531
11.125
9
Goodness of Fit



Significance of Fit for 6 b + 2 b − PseudoScalar, $m_\varphi = 20$ GeV



Other On-shell mediator scenarios

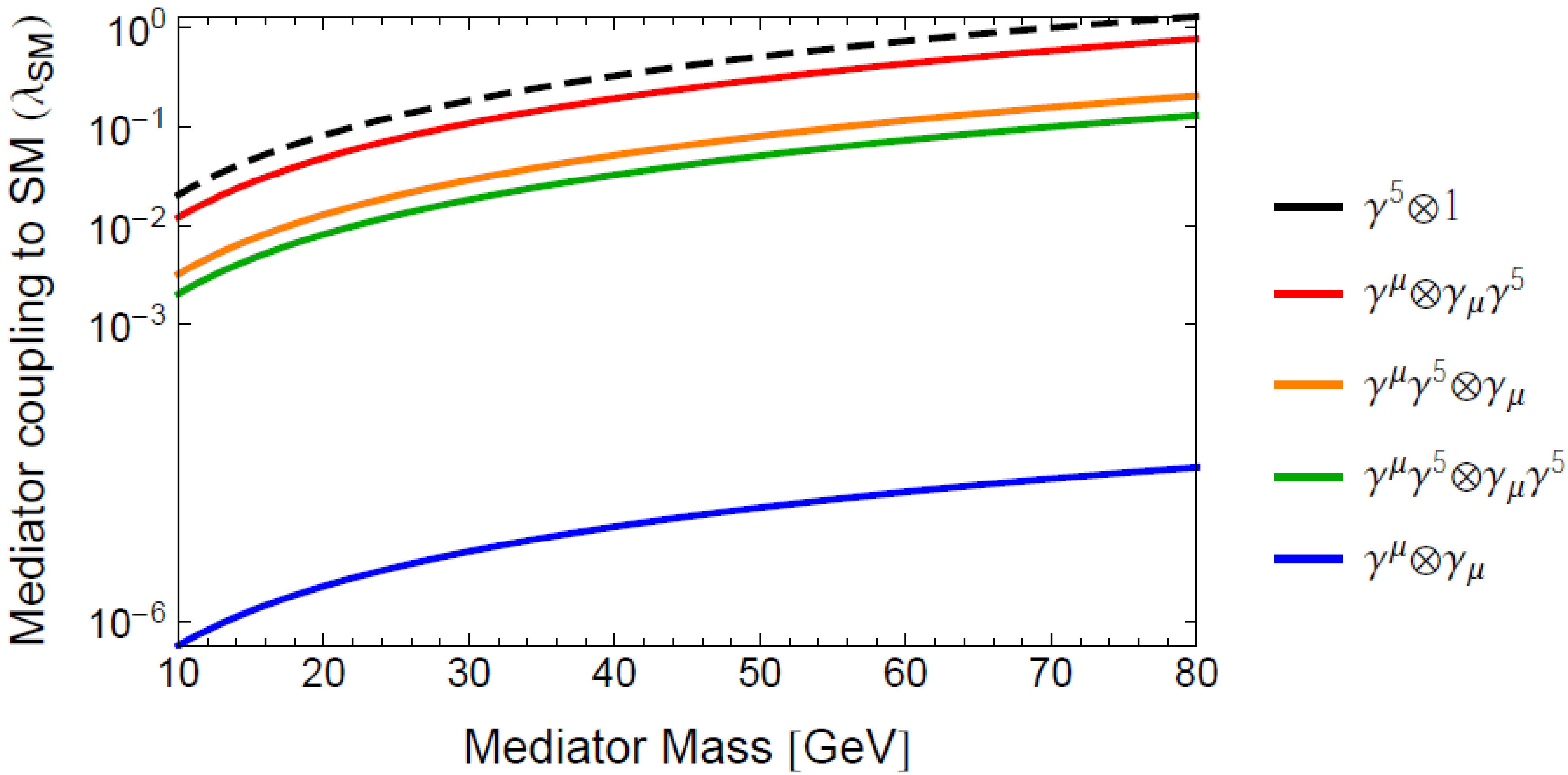
- C. Boehm, M. J. Dolan and C. McCabe arXiv:1404.4977 [hep-ph]
- P. Ko, W.-I. Park and Y. Tang arXiv:1404.5257[hep-ph]
- A. Martin, J. Shelton and J. Unwin arXiv:1405.0272 [hep-ph]

Bounds on hidden, on-shell mediators

Direct Detection

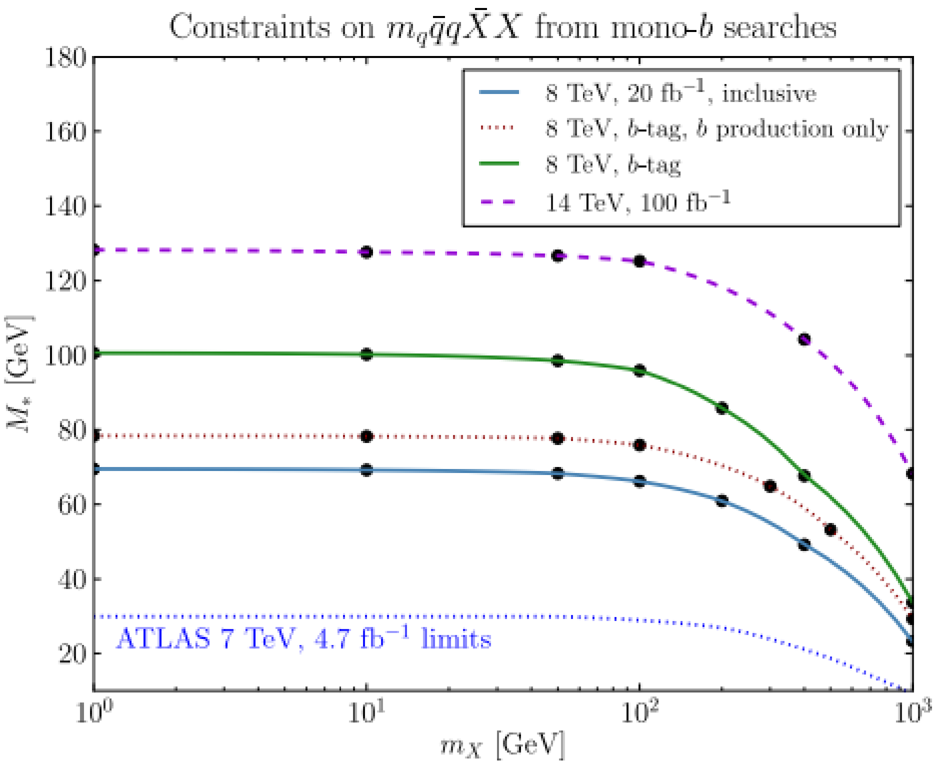
- Energy scale of direct detection experiments are on the order of 1-100 keV
- These energies allow the scattering to be parameterized as an effective theory where the relevant parameter is:

$$\frac{\lambda_{SM}\lambda_{DM}}{m_V^2} \qquad \frac{\lambda_{SM}\lambda_{DM}}{m_\phi^2}$$



Mediator coupling to SM (λ_{SM})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-6}
10
20
30
40
50
60
70
80
Mediator Mass [GeV]
$\gamma^5 \otimes 1$
$\gamma^\mu \otimes \gamma_\mu \gamma^5$
$\gamma^\mu \gamma^5 \otimes \gamma_\mu$
$\gamma^\mu \gamma^5 \otimes \gamma_\mu \gamma^5$
$\gamma^\mu \otimes \gamma_\mu$

Colliders



Collider Bounds

Projected bounds from mono b searches

$$\lambda_{\rm SM}^{\text{spin-0}} \lesssim 0.2$$

$$\lambda_{\rm SM}^{\text{spin-1}} \lesssim 0.6$$

T. Lin, E. W. Kolb and L.-T. Wang, "Probing dark matter couplings to top and bottom quarks at the LHC," Phys. Rev. D **88**, no. 6, 063510 (2013) [arXiv:1303.6638 [hep-ph]]

Opportunities for future work

- Relic Density too small

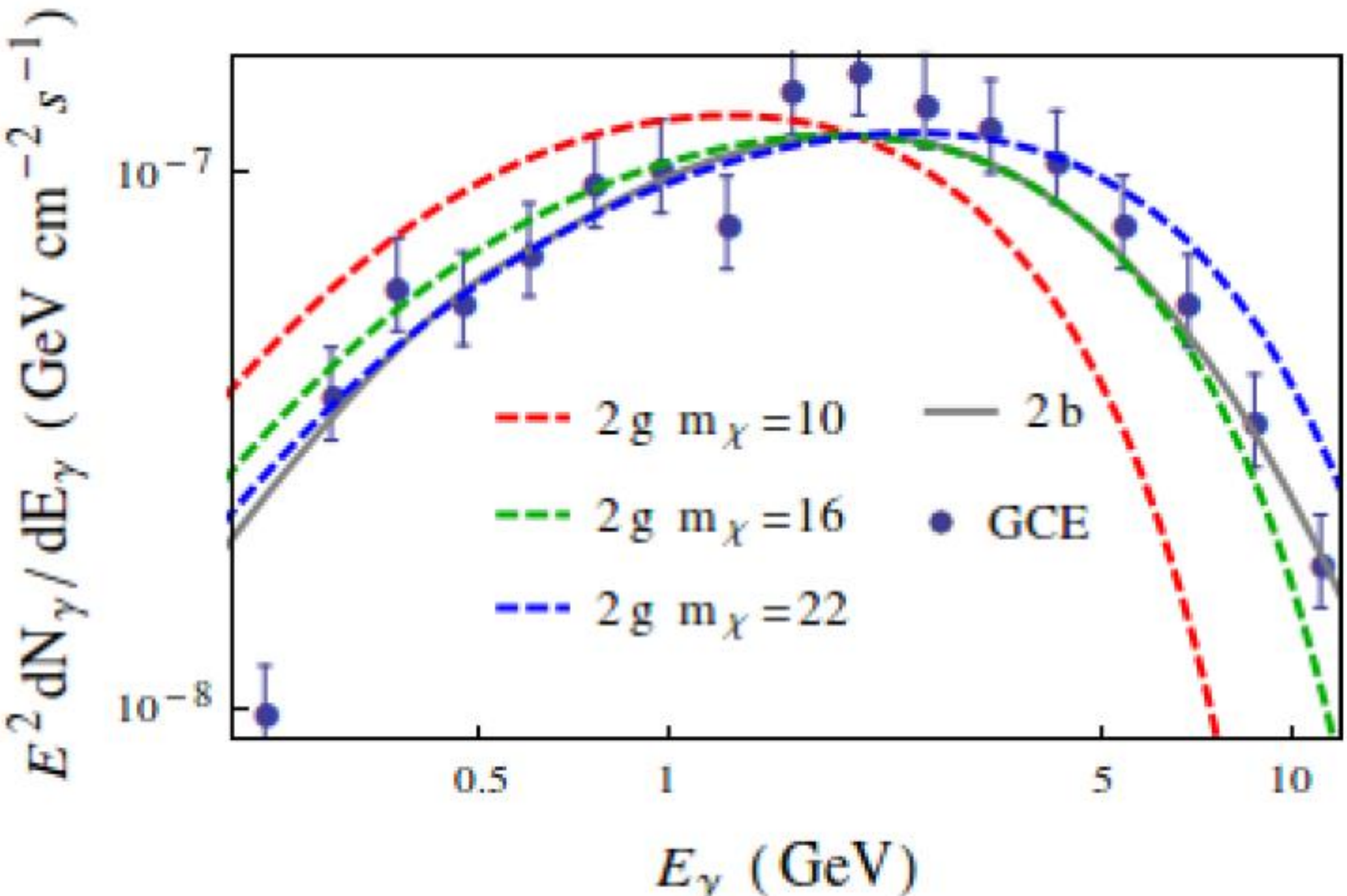
$$\frac{d\Phi(b,\ell)}{dE_\gamma} = \frac{\langle \sigma v \rangle_{b\bar{b}}}{2} \frac{1}{4\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \int_{\mathrm{LOS}} dx\, \rho^2 \left(r_{\mathrm{gal}} \left(b, \ell, x \right) \right)$$

One gets 2-3 times as many particles, but also dilutes the density by a factor of 2-3.

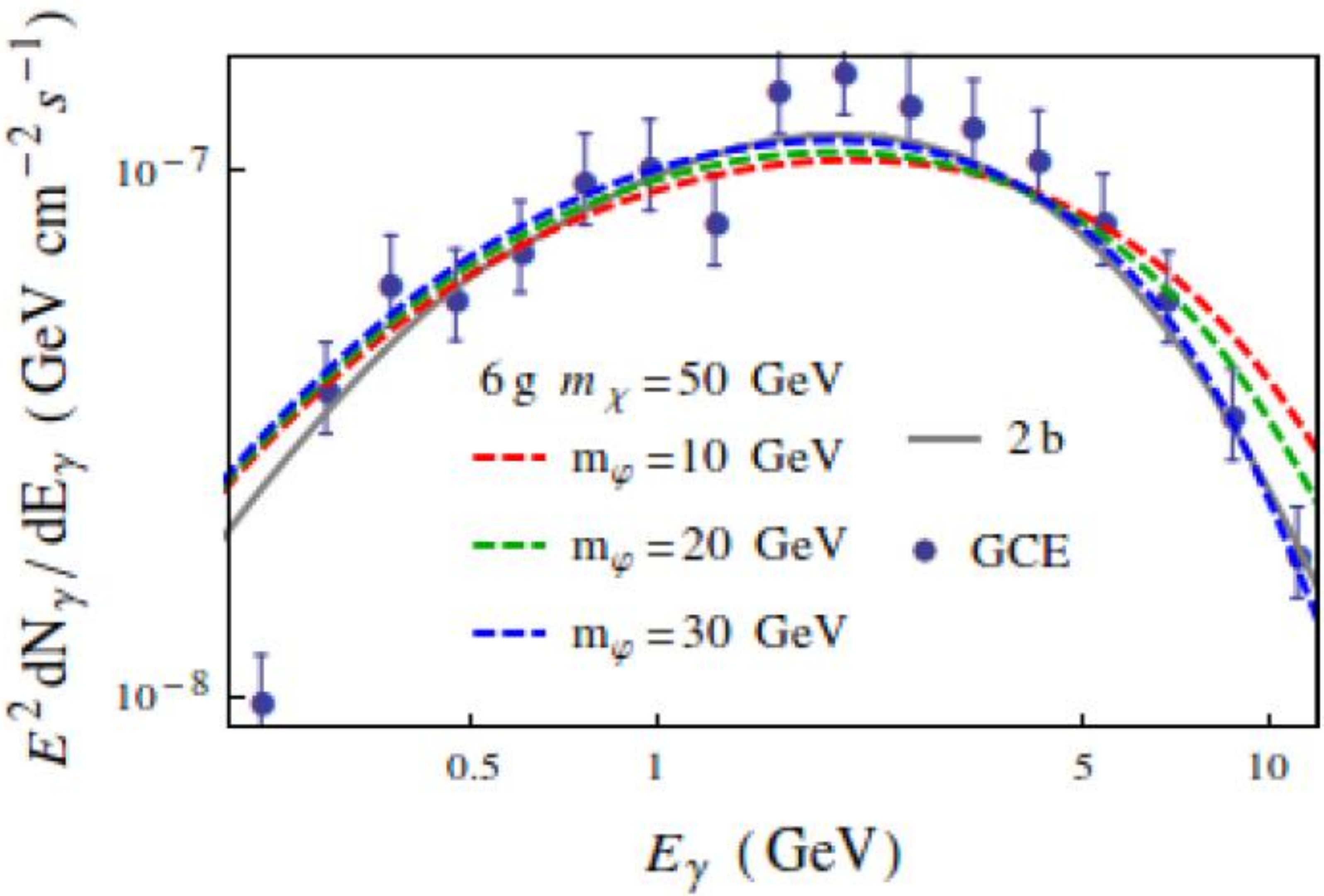
Conclusions

- On-shell mediators can be used to model the galactic center excess
  - WIMP mass 30-110 GeV
  - Excess can be explained with large amounts of freedom with regard to the standard model coupling
  - There are several experimental probes the standard model coupling

Backup Slides



$\chi\bar{\chi} \to gg$



$$\chi\bar{\chi} \to 6g$$